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Reliability of recurrence quantification analysis of postural sway data. A comparison of two methods to determine recurrence thresholds

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ABSTRACT

Ageing affects balance control resulting in a greater amplitude of sway and alterations in structure of the sway time series. Recurrence quantification analysis (RQA) has been used to determine the structure of center-of-pressure (CoP; a measure that reflects standing postural control) data as a means to quantify how CoP repeats itself / recurs below a certain threshold. This study aimed to determine how the method of threshold determination, below which a recurrence is defined, affects the within-session reliability of RQA in an elderly population.

Within-session reliability of RQA of CoP motion in the anterior-posterior and mediolateral directions was assessed in 267 individuals (>65 years old) when standing on firm or foam surface with eyes open or closed for each of two recurrence threshold methods. One threshold method sets the recurrence threshold level such that the recurrence rate is fixed to 5%, the other method sets the recurrence threshold based on 27% of the mean distance between all points from which recurrences are quantified. Reliability across four 30-s balance trials within each of four balance conditions (firm vs. foam, eyes open vs. closed) was determined using intra-class correlation, standard error of measurement and minimal detectable change.

ICCs were better, the standard error of measurement and minimal detectable change were smaller when the recurrence threshold was set to 5% using the fixed recurrence threshold. Fixing recurrence rate improves the within session reliability of RQA and could increase sensitivity to identify fall risk.

1. Introduction

Center-of-pressure (CoP) motion is commonly used to investigate postural control (Lord et al., 1991; Negahban et al., 2016; Riley et al., 1999). A goal of postural control is to regulate the center-of-mass (CoM) of the body to stay close to the upright position (Horak, 2006). This is achieved by activity of postural muscles (de Vieira et al., 2012) and is reflected in the movements of the CoP. The CoP reflects the point application of the ground reaction force of an individual standing on the ground and can be determined using a force plate. The CoP contains information on the moments generated by the postural muscles that counteract the moment due to gravity pulling on the CoM in addition to the moments that provide momentum to counteract movements of the CoM away from equilibrium (Winter, 1995). How the CoP evolves over time (i.e., dynamics) provides information regarding control of posture (Riley et al., 1999). Like any measure, the reliability of methods that quantify CoP dynamics is important for accurate interpretation, such as identification of falls risk.

Muscle activity is required to provide additional postural torque as the intrinsic mechanical stiffness of the ankle joints is not sufficient to maintain stability (Loram and Lakie, 2002). Given that muscle drive and muscle force are not linearly (non-linear) related (Farina et al., 2014) and the fact that multiple segments need to be balanced, postural sway is non-linear (Riley et al., 1999) and tends to drift within the support base or is bounded non-stationary (Carroll and Freedman, 1993; Newell et al., 1997). The main characteristic of a bounded non-stationary signal is that the mean and/or the variance of the signal changes over time (Carroll and Freedman, 1993; Newell et al., 1997) but stay within certain limits, in this case the boundaries of the support surface formed by the feet (Collins and De Luca, 1993). Standard linear methods such as the standard deviation or spectral analysis assess amplitude characteristics of the CoP. Although informative, these measures

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assume stationarity of the signals and ignore how CoP motion changes over time (i.e., the non-linear dynamical nature of CoP) thereby potentially ignoring valuable information regarding postural control.

The bounded non-stationary nature of the CoP likely reflects that a nominal upright posture is desired by the balance control system rather than the perfect upright equilibrium (Nomura et al., 2013). Limiting motion away from this equilibrium could be viewed as a recurring theme (Collins and De Luca, 1993). Methods that do not assume signal stationarity and that can assess the recurrent non-linear behaviour of the CoP could be beneficial. Recurrence quantification analysis (RQA) is a non-linear method that quantifies recurrent behaviour, does not assume signal stationarity and can be used for relatively short time series (Marwan, 2011). In addition, RQA can quantify the structure, such as regularity, of CoP dynamics (Bottaro et al., 2005; Mazaheri et al., 2010a; 2010b; Riley et al., 1999).

How CoP changes over time can be challenging to observe when CoP values are plotted against time. To visualise or extract CoP dynamics, the "method of delay" can be utilised. This method is commonly used to investigate the behaviour of dynamical systems (Eckmann and Ruelle, 1985; Packard et al., 1980). The method of delay uses the following approach; one takes values of CoP at fixed time delays (for example, 0.2 s ago, 0.4 s ago, 0.6 s ago) and these values are used as new coordinates in a multidimensional space, also referred to as phase space (Takens, 1980). See Fig. 1 for an example or see the recurrence-plot.tk website (http://www.recurrence-plot.tk/glance.php?show_intro=1, Marwan et al., 2007) for a visual explanation of this concept. The underlying dynamics of the CoP is then represented as a geometrical shape of the data after many coordinates are plotted in this phase space describing the overall dynamical behaviour. How the signal recurs, i.e., visits the same points within this phase space is assessed by RQA (Marwan, 2003).

A crucial parameter of RQA is the recurrence threshold level below which a recurrence is defined (Marwan, 2011). Different methods have been utilised to determine the recurrence threshold such as percentage of the maximum diameter of the geometrical shape in phase space (Decker et al., 2015; Ramdani et al., 2013) or a percentage of the mean distance between all data points in phase space (Riley et al., 1999; Riley and Clark, 2003). However, these normalisation methods could be biased by a few large CoP motion excursions and the CoP could recur more in some areas than other areas in phase space. This would increase variability of the number of observed recurrences and therefore also increase the variability of RQA output variables between trials and negatively impact reliability. We argue that adjusting the recurrence threshold that fixes the recurrence rate would improve reliability of RQA of CoP.

Only one study has assessed the reliability of RQA of CoP motion during standing balance (Mazaheri et al., 2010a). Mazaheri et al. (2010a) based the recurrence threshold on a percentage of the maximum diameter of the reconstructed geometrical shape in phase space. They observed poor reliability of recurrence rates (intraclass correlation coefficients [ICC] ranged between 0.03 and 0.40 depending on the balance task), which supports the above argument. Nevertheless, this study observed good-to-excellent reliability of some RQA outcome variables. The reliability of some other important RQA variables, such as the mean durations of regular features, were not investigated.

This study aimed to determine the within session reliability of RQA of CoP motion in the anterior-posterior (AP) and medial–lateral (ML) directions, with recurrence thresholds set based on amplitude (percentage of mean distance between all data points in phase space) and set such that the percentage of recurrences was fixed at 5%. Repeatability of RQA of four repetitions was examined in individuals older than 65 years of age under four levels of postural difficulty.

2. Methods

2.1. Participants

Participants older than 65 years of age (124 females, 143 males) volunteered for a prospective study on falls. The mean ± SD age, height, weight of participants was 75 ± 6 years, 1.68 ± 0.09 m, and 74.9 ± 14.7 kg, respectively. Participants were recruited from the Brisbane metropolitan area via the Australian electoral role. Participants were excluded if they had an ocular disease, recent or recurrent history of musculoskeletal injury and/or surgery, were unable to ambulate independently without the use of a walking aid, exhibited any neurological disorders (e.g., Parkinson's Disease) or were cognitively impaired [i.e., Mini mental state exam score < 24 (Folstein et al., 1983)]. Participants provided written informed consent. The experimental protocol was approved by the Institutional Human Research Ethics Committee and conformed to the Declaration of Helsinki.

2.2. Experimental setup

Balance was assessed using a force plate (AMTI, OR6-6, Watertown, MA, US), digitized with 16-bit precision at 1000 samples/s using a Vicon Mx Giganet and Vicon Motus software (v9.2.0; Vicon, Oxford, UK). The force plate was placed in the middle of a 10×16 m room.

Participants performed four balance conditions while standing barefoot with feet at shoulder width apart on the force plate (firm surface) or standing barefoot on a $60 \times 60 \times 15$ cm medium density foam rubber surface (Lord et al., 2003) with either eyes open or blindfolded, in randomized order. During the eyes open condition, participants looked at a fixed point at eye height on a wall partition that was placed at 5 m distance in front of the participant. Participants were asked to stand as still as possible with the arms hanging by their side. Data collection started after ~ 10 s of standing and continued for 30 s. Each condition was repeated four times consecutively. Participants rested for ~ 30 s while seated in between trials within each condition. The four trials within each balance condition were used to assess the within-session reliability (see 2.4. Statistical analysis below).

2.3. Data analysis

Data were analysed using Matlab (R2017a, Mathworks inc., Natick, MA, USA). CoP data were filtered with a bi-directional, second order low pass Butterworth filter. The cut-off frequency was set at 20 Hz; bi-directional filtering increased the filter order to 4. CoP data were then decimated to 100 samples/s.

Recurrences were quantified using Marwan's Matlab toolbox, version 5.21, release 31 (Marwan, 2003; Marwan et al., 2007). Four time-delayed copies of the original CoP signal were created to form a 5D phase space (Fig. 1), determined with a false nearest neighbour analysis (Kennel et al., 1992). The delay was determined using the average displacement method (Rosenstein et al., 1994) separately for each 30 s CoP signal. This phase space contains the observed CoP reflected by the time-delayed copies and can revisit or recur previous observations using a pre-set recurrence threshold. Recurrences can be visualized using a 2-dimensional recurrence plot (Fig. 1D, Eckmann et al., 1987).

Diagonal and vertical lines can be identified in the recurrence plot. Recurrences that form diagonal lines reflect CoP motion that run parallel in phase space (see Fig. 1C, green lines). In other words,

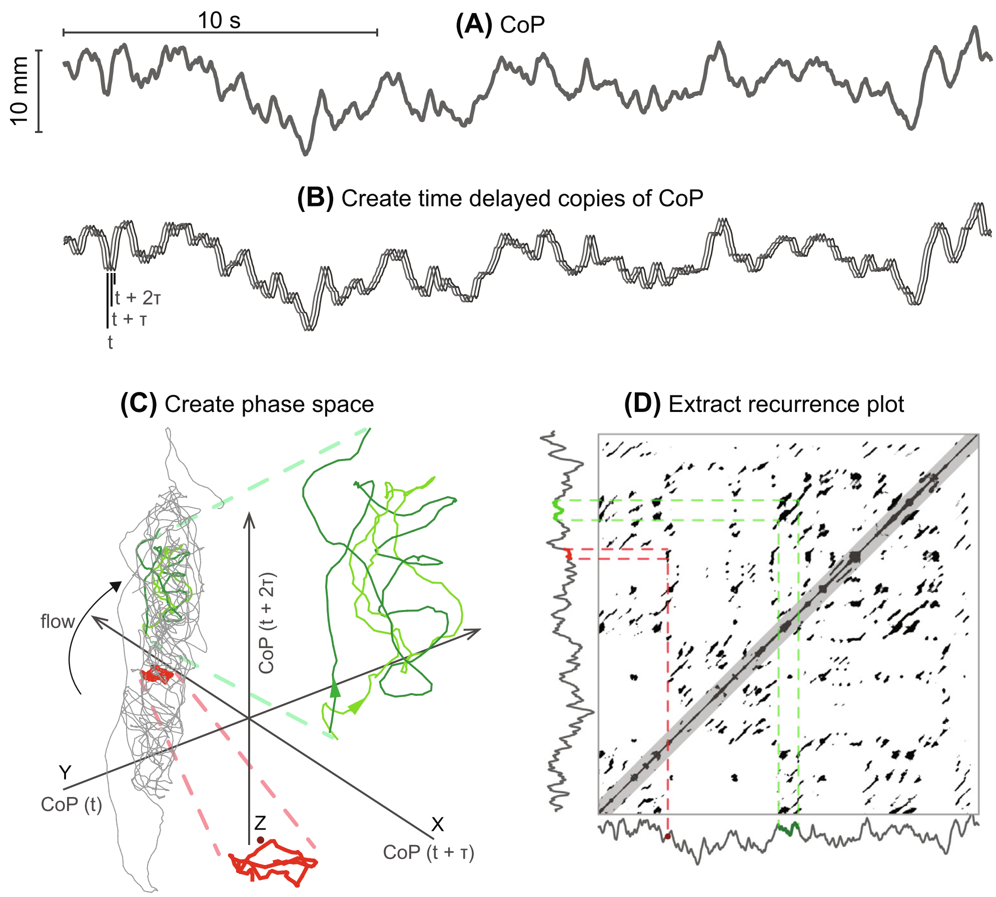

Fig. 1. Visualisation of the recurrence quantification analysis method. (A) Center-of-pressure (CoP) motion (30 s) in anterior-posterior direction, example of an elderly individual standing on firm with eyes open. (B) Delay-embedding with tau (τ) of 21 samples. Delayed copies of CoP motion are used to provide a geometrical representation of CoP dynamics. (C) A phase space is created by plotting the delayed CoP copies against each other. Note that the example is given in 3D, but analysis was performed in 5D. (D) The recurrence plot represents the recurrences of CoP in the phase space depicted in (C); by creating a 2D recurrence plot by adapting the recurrence threshold distance to fix the recurrence rate to 5%. Temporally close recurrences were excluded (<1 s, Theiler window) which is represented by the greyed area along the line of identity (were CoP recurs with itself). Two examples are shown that represent a diagonal (in light and dark green) and vertical recurrence structures (in red). These examples are also shown in the zoomed in views in the phase space in (C). The light and dark green represents CoP motion running parallel in phase space and the red line represents CoP motion that revisits and remains in a region in phase space represented by the red dot in (C) and (D). The time series to the left and underneath the recurrence plot represent the CoP motion and provides an indication where the highlighted (green and red) recurrences occurred. Note these locations are approximations as recurrences were determined in a 5D phase space. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

diagonals reflect CoP motion that shows similar amplitude and changes in amplitude over time compared to CoP dynamics at other time points, i.e., a repetition of the dynamical behaviour. Because CoP motion sections are temporally and spatially similar, these diagonal line sections in the recurrence plot reflect the deterministic (DET)/regular behaviour (Fig. 1).

Recurrences that form vertical lines reflect CoP motion that recurs in phase space, but then remains close for some time, and reflect stationary or laminar (LAM) behaviour. From time to time, CoP motion exhibits periods that are relatively stationary in time, i.e., does not change much in amplitude (see Fig. 1C, red lines section). These stationary periods could be viewed as a temporary hold of the CoM in which the torque generated by the postural muscles matches that of the torque generated due to gravity pulling on the CoM of the body (Bottaro et al., 2005).

We extracted the percentage recurrences that formed diagonal and vertical lines of longer than 0.1 s (%DET, %LAM, respectively), the mean of these horizontal and vertical lines (L_{mean}, Trapping time [TT], respectively), and the maximum diagonal line length (L_{max}).

The recurrence threshold was determined in two ways. First, the threshold level was set to 27% of the mean distance between all points in phase space, which on average created 5% recurrence rate across all participants and balance conditions, referred to as: *amplitude threshold*. Second, the threshold level was set such that the recurrence rate was fixed at 5%, referred to as *fixed recurrence threshold*.

It is important to exclude CoP that recurs simply because data points are close in time (Marwan, 2011). This is done by applying a time period (Theiler window) that excludes recurrences that are temporally close, reflected by the greyed-out area in the recurrence plot of Fig. 1D. Temporally close recurrences within 1 s were excluded in both methods.

2.4. Statistical analysis

The ICC determined the within session test–retest reliability of RQA between four 30 s trials during each balance condition (McGraw and Wong, 1996). ICC (95% confidence interval [CI]) estimates were based on a mean-rating (k = 4), absolute agreement, 2-way fixed effects model (Koo and Li, 2016; McGraw and Wong, 1996). ICC values of < 0.4, between 0.4 and < 0.6, between 0.6 and < 0.75, and > 0.75 were classified as poor, fair, good, and excellent, respectively (Cicchetti, 1994). The standard error of measurement (SEM) of each measure was calculated using the square root of the mean square error term obtained with the 2-way analysis of variance table that was used to determine the ICC values (de Vet et al., 2006). This SEM represents the within-subject variability of the repeated measures and is equal to the pooled standard deviation of the pairwise differences between the four repetitions divided by $\sqrt{2}$ (Franz and Loftus, 2012). This method of calculating the SEM represents the consistency of the measure when repeated. The SEM can be used to estimate a confidence interval of the expected differences between repeated measures also referred to as the minimal detectable change (MDC) (de Vet et al., 2006; Franz and Loftus, 2012). The 95% confidence interval MDC_{95} was calculated as follows; $MDC_{95} = 1.96 \times SEM \times \sqrt{2}$. Test-retest reliability of the recurrence rate could only be tested when recurrence threshold was based on the *amplitude* as the recurrence rate was fixed when using the *fixed recurrence threshold*.

3. Results

Because of technical issues, data were not recorded from 2, 1, 1, 1 participant(s) during Firm EO, Firm EC, Foam EO, and Foam EC,

Table 1
Mean (standard deviation) values of elderly individuals' balance control using the diagonal line features of recurrence quantification analysis.

Method	Condition	Variable	rep 1	rep 2	rep 3	rep 4	SEM	MDC_{95}
Fixed recurrence threshold	Firm EO		89.4 (5.7)	87.8 (6.4)	87.3 (7.9)	88.1 (7.5)	2.6	7.2
	Firm EC		88.9 (6.0)	89.0 (6.1)	89.2 (6.1)	89.5 (5.8)	2.4	6.8
	Foam EO		93.4 (3.1)	93.5 (3.0)	93.6 (3.0)	93.5 (3.5)	1.8	4.9
	Foam EC		92.9 (3.4)	93.1 (3.2)	93.3 (3.1)	93.2 (3.3)	1.5	4.3
		%DET						
Amplitude threshold	Firm EO		87.9 (8.1)	85.6 (9.2)	85.1 (11.4)	86.4 (11.1)	4.2	11.6
	Firm EC		87.5 (8.8)	87.7 (9.1)	88.5 (8.1)	88.7 (8.2)	4.4	12.1
	Foam EO		92.1 (4.3)	92.8 (4.2)	93.0 (4.2)	93.1 (4.4)	3.5	9.6
	Foam EC		91.1 (5.1)	92.0 (4.5)	92.2 (4.5)	92.5 (4.7)	3.2	8.9
Fixed recurrence threshold	Firm EO		0.396 (0.085)	0.383 (0.086)	0.385 (0.099)	0.399 (0.102)	0.047	0.130
	Firm EC		0.362 (0.071)	0.384 (0.093)	0.390 (0.086)	0.401 (0.103)	0.039	0.108
	Foam EO		0.395 (0.070)	0.404 (0.076)	0.409 (0.081)	0.420 (0.092)	0.039	0.109
	Foam EC		0.377 (0.061)	0.379 (0.065)	0.384 (0.066)	0.387 (0.070)	0.032	0.088
		L_{mean} (s)						
Amplitude threshold	Firm EO		0.393 (0.123)	0.375 (0.137)	0.377 (0.122)	0.414 (0.164)	0.112	0.311
	Firm EC		0.363 (0.104)	0.390 (0.135)	0.403 (0.134)	0.412 (0.144)	0.078	0.216
	Foam EO		0.384 (0.102)	0.405 (0.108)	0.414 (0.113)	0.427 (0.137)	0.077	0.214
	Foam EC		0.359 (0.086)	0.372 (0.094)	0.379 (0.099)	0.393 (0.123)	0.049	0.136
Fixed recurrence threshold	Firm EO		2.274 (0.714)	2.240 (0.680)	2.251 (0.736)	2.315 (0.762)	0.490	1.359
	Firm EC		1.985 (0.574)	2.138 (0.622)	2.214 (0.649)	2.275 (0.672)	0.451	1.250
	Foam EO		2.126 (0.561)	2.151 (0.605)	2.164 (0.589)	2.237 (0.689)	0.421	1.166
	Foam EC		2.027 (0.467)	2.031 (0.562)	2.072 (0.514)	2.145 (0.609)	0.402	1.113
		L_{max} (s)						
Amplitude threshold	Firm EO		2.248 (0.940)	2.173 (0.965)	2.167 (0.928)	2.328 (1.101)	0.788	2.184
	Firm EC		2.002 (0.841)	2.150 (0.846)	2.268 (0.847)	2.320 (0.871)	0.647	1.794
	Foam EO		2.030 (0.750)	2.125 (0.731)	2.188 (0.742)	2.263 (0.951)	0.649	1.798
	Foam EC		1.888 (0.650)	1.973 (0.710)	2.010 (0.735)	2.138 (0.830)	0.478	1.325

Data are reported for the diagonal line features of recurrence quantification analysis (percentage determinism [%DET], mean and maximum diagonal line length [L_{mean}, L_{max}, respectively]) during standing on firm and foam surface with eye open (EO) or eyes closed (EC) using two separate recurrence threshold methods: *fixed recurrence threshold*, a threshold that fixes the recurrence rate [rr] percentage to 5%; *amplitude threshold,* a threshold based on 27% of mean distance between all point in phase space. The standard error of measure (SEM) and the minimal detectable change (MDC_{95}) reflecting the expected variability between the 4 repetitions are also reported.

Table 2
Mean (standard deviation) values of elderly individuals' balance control using the vertical line features of recurrence quantification analysis.

Method	Condition	Variable	rep 1	rep 2	rep 3	rep 4	SEM	MDC_{95}
Fixed recurrence threshold	Firm EO		93.6 (3.8)	92.7 (4.4)	92.3 (5.1)	92.8 (5.0)	2.2	6.0
	Firm EC		92.9 (4.1)	93.3 (3.9)	93.4 (4.0)	93.7 (3.8)	2.3	6.4
	Foam EO		95.7 (2.2)	96.0 (2.0)	96.0 (2.0)	96.1 (2.2)	2.2	6.2
	Foam EC		95.0 (2.7)	95.3 (2.4)	95.6 (2.3)	95.5 (2.7)	2.2)	6.4
		%LAM						
Amplitude threshold	Firm EO		92.3 (6.2)	91.0 (6.5)	90.6 (8.0)	91.6 (8.2)	3.7	10.3
	Firm EC		91.5 (6.7)	92.2 (6.4)	92.9 (5.5)	93.0 (5.7)	4.7	12.9
	Foam EO		94.4 (3.9)	95.2 (3.4)	95.4 (3.2)	95.6 (3.3)	4.4	12.2
	Foam EC		92.8 (5.1)	94.0 (4.0)	94.3 (4.2)	94.6 (4.2)	4.9	13.7
Fixed recurrence threshold	Firm EO		0.366 (0.099)	0.357 (0.096)	0.365 (0.109)	0.383 (0.115)	0.058	0.162
	Firm EC		0.323 (0.083)	0.357 (0.103)	0.372 (0.104)	0.379 (0.111)	0.049	0.134
	Foam EO		0.343 (0.085)	0.358 (0.092)	0.369 (0.101)	0.385 (0.111)	0.047	0.131
	Foam EC		0.315 (0.074)	0.326 (0.078)	0.336 (0.076)	0.347 (0.090)	0.037	0.103
		TT (s)						
Amplitude threshold	Firm EO		0.367 (0.148)	0.353 (0.160)	0.361 (0.138)	0.404 (0.186)	0.137	0.379
	Firm EC		0.329 (0.125)	0.386 (0.156)	0.390 (0.157)	0.398 (0.165)	0.097	0.269
	Foam EO		0.333 (0.123)	0.360 (0.131)	0.378 (0.137)	0.396 (0.161)	0.093	0.258
	Foam EC		0.298 (0.104)	0.324 (0.119)	0.335 (0.119)	0.358 (0.153)	0.059	0.164

Data are reported for the vertical line features of recurrence quantification analysis (percentage laminarity [%LAM], mean vertical line length or trapping time [TT]) during standing on firm and foam surface with eye open (EO) or eyes closed (EC) using two separate recurrence threshold methods: *fixed recurrence threshold*, a threshold that fixes the recurrence rate [rr], percentage to 5%; *amplitude threshold,* a threshold based on 27% of mean distance between all point in phase space. The standard error of measure (SEM) and the minimal detectable change (MDC_{95}) reflecting the expected variability between the 4 repetitions are also reported.

respectively. There were<4 repetitions available from 2, 2, 6, and 3 participants during Firm EO, Firm EC, Foam EO and Foam EC, respectively. Four participants were unable to perform Foam EC. These data were not included in further analysis. Mean values (SD) of the RQA measures using either *amplitude threshold* or *fixed recurrence threshold* method for each repetition and balance condition and the SEM are reported in Tables 1 and 2.

Overall, the ICC values of RQA were higher when using the *fixed recurrence threshold* than *amplitude threshold* in both AP and ML directions, except for L_{max} (Fig. 2). The recurrence rate ICC values of *amplitude threshold* were 'moderate' to 'good' during standing on Firm and were 'good' when standing on Foam (Fig. 3) with a SEM of 2.4, 1.8, 1.9, 1.4% and MDC_{95} of 6.6, 5.1, 5.1, and 3.8% during Firm EO, Firm EC, Foam EO, and Foam EC, respectively. The overall higher ICC values (except for L_{max}) of reported RQA measures with *fixed recurrence threshold* than *amplitude threshold* resulted in lower SEM and MDC_{95} values as presented in Table 1 and Table 2 for the diagonal and vertical line features, respectively.

4. Discussion

The results indicate that fixing the recurrence rate results in better test–retest reliability of RQA outcomes than using a threshold based on the amplitude of the signal. Better reproducibility of measures would increase the sensitivity and specificity when used for classification or prediction, such as classification of indi-

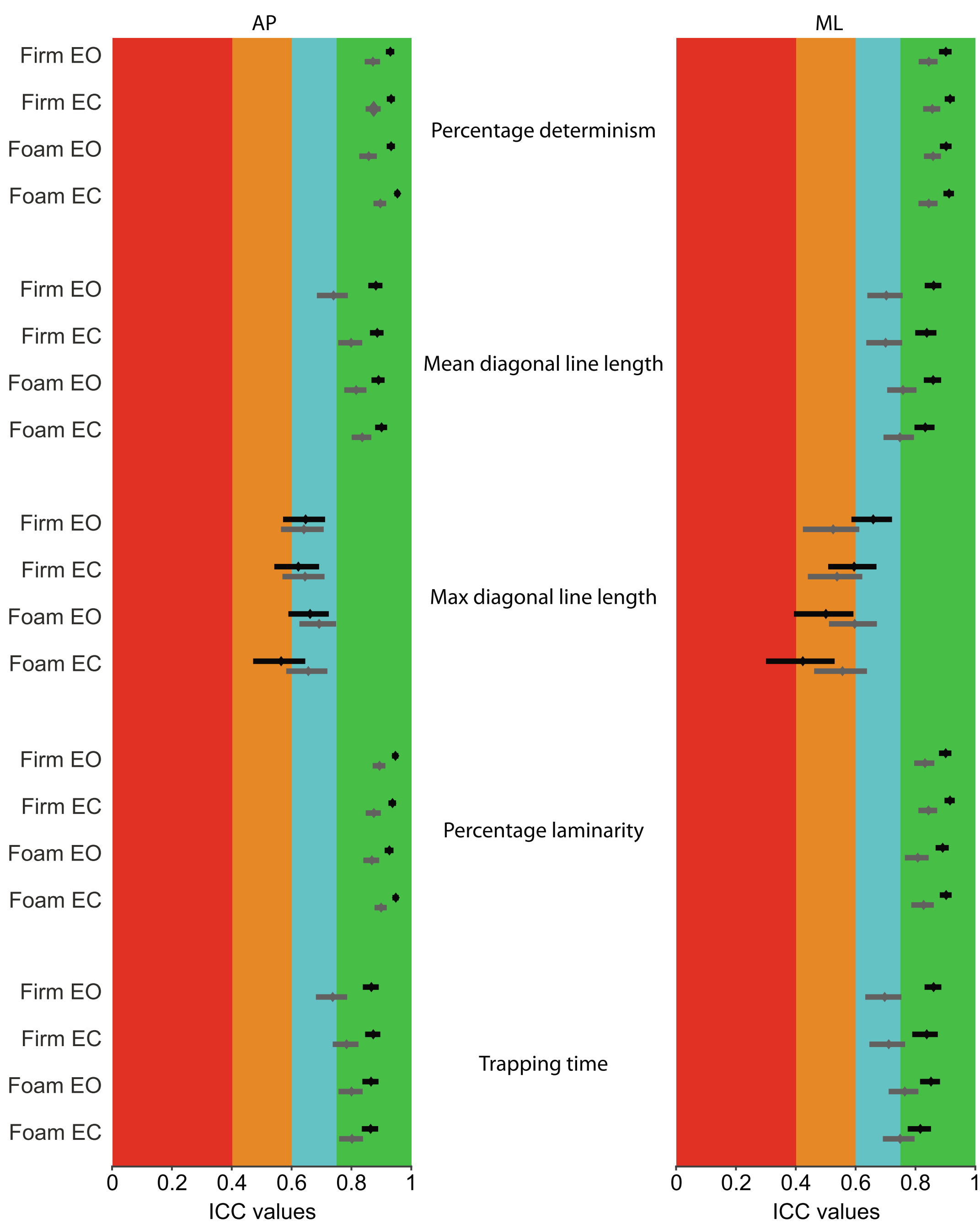

Fig. 2. Intraclass correlation (ICC) values (95% CI) of recurrence quantification (RQA) measures based on fixed recurrence rate (5%, in black) and based on percentage of mean distance in phase space (in grey) in the anterior-posterior (AP, left) and medial–lateral direction (ML, right). The ranges of ICC colors; red, orange, blue, or green, are considered as 'poor', 'moderate', 'good', or 'excellent', respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

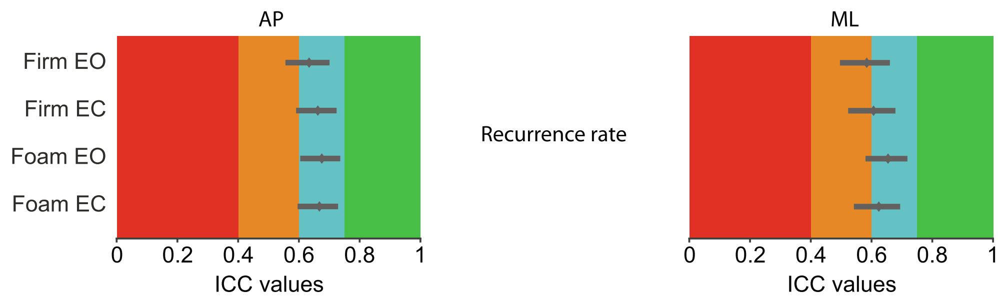

Fig. 3. Intraclass correlation (ICC) values (95% CI) of the recurrence rate when recurrence threshold based on percentage of mean distance in phase space in the anterior-posterior (AP, left) and medial–lateral direction (ML, right).The ranges of ICC colors; red, orange, blue, or green, are considered as 'poor', 'moderate', 'good', or 'excellent', respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

viduals with and without pathology (e.g., Parkinson's decease) or falls risk.

It is challenging to make appropriate choices for the RQA input parameters, as they will impact the RQA output values (Marwan, 2011) and may affect reliability. For example, for the same CoP signal, a higher recurrence threshold would result in longer diagonal line features in the recurrence plot and vice versa. It is therefore common to relate the recurrence threshold to the amplitude of the CoP signal. This is done for two main reasons; i) to avoid too many or too few recurrences in the recurrence plot which would challenge the interpretation related to the recurrent behaviour of the signal, and ii) the recurrence threshold is linked to the amplitude of the CoP signal to assess the dynamical behaviour independently from its amplitude. However, setting the recurrence threshold as a percentage of the mean distance between all points in phase space did not result in satisfactory reliable recurrence rates as shown by Mazaheri et al., (2010a) and our findings. We argue that by fixing the recurrence rate, temporal dynamics are made less dependent on its amplitude than an amplitude-based recurrence threshold method. Fixing the recurrence rate might therefore allow for better comparison between participants, groups or balance conditions, but further research should confirm this.

Fixing the recurrence rate does improve the reliability of the RQA measures. However, this precludes the use of recurrence rate as an outcome measure. Recurrence rate itself is likely to be of little interest as the diagonal and vertical line features that emerge from these recurrences reflect the underlying dynamical behaviour of CoP not the recurrence rate itself. Therefore, fixing recurrence rate would not affect overall interpretability of RQA.

That there are no clear guidelines for selecting input parameters for RQA is highlighted by the varying number of phase space dimensions used to investigate CoP dynamics in previously published papers. For example, Riley et al., (1999) opted for a 10D phase space, whereas other authors have used a 7D (Pellecchia and Shockley, 2005), 8D (Decker et al., 2015; Schmit et al., 2006), or 12D (Coubard et al., 2014) and some used a 5D phase space dimension (Mazaheri et al., 2010b; Negahban et al., 2010). It is important not to choose a larger phase space dimension than strictly necessary as data becomes more correlated in phase space with increasing dimensions (Grassberger and Procaccia, 1983; Marwan, 2011). This will bias CoP signals to be more regular. On the other hand, the underlying dynamics of the system might not be fully revealed if a phase space dimension is selected that is lower than required. However, also numerical considerations should be taken into account (Marwan, 2011), for example, to be able to detect a 5D or 6D geometrical shape in phase space, ~1800 (18 s at 100 samples/s) or ~ 8000 samples (80 s at 100 samples/s) is advised, according to Grassberger & Procaccia (1983) described by Marwan (2011). Data length required exponentially increases with the number of dimensions to be detected (Marwan, 2011). Although this Grassberger & Procaccia algorithm (Grassberger and Procaccia, 1983) is derived from dynamical systems that are governed by known non-linear equations, not CoP, it does highlight that careful considerations must be given when deciding on the number of phase space dimensions taking into account the available time duration of the CoP signal. We opted for a fixed 5D phase space taking into consideration the 30 s duration of the CoP signals, results of the false nearest neighbour analysis, and potential bias of RQA outcome measures when not fixing the phase space dimensions between different CoP signals. The latter would negatively impact reliability of RQA outputs. However, we do not believe that a different choice of a fixed phase space dimension would impact the findings of our study.

The ICC of the recurrence rate using the *amplitude threshold* ranged from 'moderate' to 'good' and was higher than the within session reliability findings of Mazaheri et al. (2010a). Direct comparison between studies is challenging because of differences in methodology. For example, differences in sample size, included age range, standing balance instructions, and number of included repetitions. 'Moderate' to 'good' test–retest reliability of recurrence rate, rather than higher ICC values, might be explained by the relatively short duration of the balance trials (30 s), or the variable nature of CoP motion. Although large fluctuations might be part of the behaviour, these affect the recurrence threshold and therefore the test–retest reliability of the measure.

We assessed the test–retest reliability of L_{mean}, L_{max} and TT, which had not been assessed before for standing balance. These are important measures as they reflect the predictable (regular) and stationary (laminar) behaviour of CoP motion. Predictable behaviour could reflect stable behaviour or behaviour that reflects slow pendulum-like movements of the CoM which are regular and predictable. Laminar behaviour likely requires good control of posture as it could reflect a temporary balance between postural and gravitational moments. The ICC values of these measures were lower than the percentage of these features (%DET and %LAM) in relation to all recurrences. L_{max} reliability exhibited the lowest ICC values of all investigated RQA measures and no clear difference between the two recurrence threshold methods was observed. L_{max} is simply the longest diagonal line in the recurrence plot, excluding temporally close recurrences. Because L_{max} lies at the extreme end of the diagonal line length distribution it is more likely to be susceptible to variability between trials within participants.

Some limitations require consideration. Reliability was assessed within one session. It is unclear whether these measures are consistent between balance assessments with longer time intervals. Findings can only be extrapolated to relatively healthy elderly population testing 4 repetition of 30 s using the proposed methods. However, we expect differences between threshold methods to be consistent. The consistency of balance control might be affected with age (Woollacott, 1993). Although we did not assess the reliability across different age groups above 65 years, advanced age may have affected the reliability of the RQA measures. Impact of balance inconsistency was limited due to the short rest duration in between trials but might have larger impact on reliability if time intervals between tests are longer.

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Conflict of interest statement

None

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